

# THREE-DIMENSIONAL PRESSURE PATTERN OF THE DALLAS TORNADO AND SOME RESULTANT IMPLICATIONS

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## ABSTRACT

The three-dimensional pressure field of the Dallas tornado, April 2, 1957, is integrated from a distribution of observed tangential wind speeds. A total pressure drop of 60 mb. is computed at ground level at the axis. Variations in tornado funnel geometry are explained by changes in moisture content of the involved air and system-wide pressure changes. The effects of the moving pressure field on hypothetical vented and unvented buildings are computed. The results indicate that a dwelling, which could lose in 5 seconds about 75 percent of an imposed pressure difference, would most likely not yield due to internal pressure alone, if the imposed pressure difference were like that of the Dallas tornado.

## 1. INTRODUCTION

In an earlier study [1] the tangential wind speed distribution of the Dallas tornado of April 2, 1957 was derived by tracking pieces of debris, cloud tags, and dust parcels that were photographed in movies of that tornado. Principles of photogrammetry [2] were used in scaling the movies from which these data were taken. In order to get the greatest possible coverage of data points in the space occupied by the tornado it was necessary to take speed measurements over 19 minutes of the tornado's lifetime. The data distribution extended to a height of 1700 feet and a radius of 1500 feet except below 1000 feet in elevation where traceable particles extended only to between 400 and 900 feet in radius. Using the tangential speed ( $v$ ) distribution as analyzed in figure 2 of [1] and making use of the cyclostrophic wind equation,

$$\partial p / \partial r = \rho v^2 / r \quad (1)$$

(where  $p$  is pressure,  $r$  radial distance, and  $\rho$  density) a distribution of values of horizontal pressure gradient in terms of millibars per meter was obtained for every 100-foot level for the region occupied by the tornado described above. Of course, it is realized that some limitations are imposed by the assumption of cyclostrophic balance and steady state, especially in the inflow region near the ground; however, at present no reasonable allowance for resistance and accelerational forces has been developed for this situation. Other writers (e.g., Long [3], Glaser [4]) have justified the use of the cyclostrophic equation in their studies of vortex motion.

In that part of the material following which deals with vented and unvented structures, it is not implied that the pressure distribution arrived at and its implications are more important than the aspects of tornado wind force on structures. Rather, one side of the problem is presented,

that is, the effects of variable rates of static pressure drop on structures.

## 2. THE DERIVED PRESSURE FIELD

The pressure field was derived by integrating equation (1) horizontally from the 1,500-foot radius, step-wise, to near the axis for each 100-foot level. For the boundary condition at the 1,500-foot radius, a vertical lapse rate of pressure computed from the pressure and temperature conditions at Dallas for the time of the tornado, was used. The resulting pressure distribution, delineated by isobars at every 5 mb., is shown as figure 1. In general the isobaric surfaces dip away from the horizontal going toward the axis.

One more assumption must be mentioned: in the region below the 400-foot level, any computed distribution of pressure values that tended to inflect the tornado's isobaric surfaces toward the axis was shifted outward enough to keep the sign of curvature yet conserve the horizontal rate of change of pressure. The earlier-derived distribution of tangential speeds would have caused a bending toward the axis of the pressure surfaces below 400 feet but because the observed speeds must have been retarded by frictional drag of the ground, it was reasoned that the region of steep pressure gradient continued down to the ground without inflection. Of course, at very small radii, the isobaric surfaces must have curved toward the axis because of the reduced tangential speed there.

The total pressure drop at the ground estimated by this method was almost 60 mb., or just under 6 percent of an atmosphere. One might add 2 or 3 mb. if the pressure reference were taken entirely away from the influence of the tornado, for example, two or three miles. Since most of the wind speed values from which the pressure change computations were made were derived during an immature

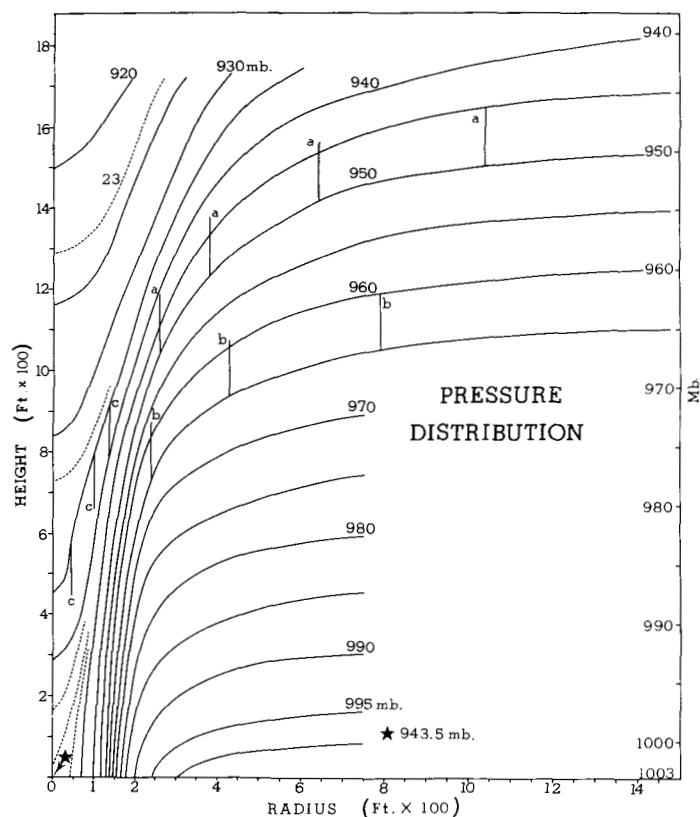


FIGURE 1.—The derived pressure field of the Dallas tornado in the vertical plane. Symmetry in the horizontal plane is assumed, giving pressure distribution in three dimensions. The derived central pressure at the ground is 943.5 mb., or 59.5 mb. below the undisturbed pressure of 1003.0 mb.

stage of the tornado, that is, when the tip was suspended aloft, it is suspected that the total pressure drop computed here was exceeded at a later stage of the tornado's development.

### 3. IMPLICATIONS OF THE PRESSURE FIELD

As can be seen in figure 1, the pressure surfaces slope downward gently at the larger radii, then curve more steeply at smaller radii. A particularly interesting feature of the pressure field is that the vertical spacing of the pressure surfaces decreases with decreasing radius to a certain limiting radius. The vertical bars a and b show this feature rather clearly since each set has the same length. If one can safely assume that the vertical spacing at the 1,500-foot radius represents hydrostatic equilibrium, then the closer vertical spacing at smaller radii indicates the presence of a net upward force. This interpretation is valid as long as increased density does not overcome the upward force indicated by the closer spacing, but considering the 60-mb. pressure drop at the axis, it is unlikely that the density is higher there. This closer vertical spacing is to be expected in the tornado where upward current speeds are greatest nearer the center and where

upward accelerations are occurring. At the smaller radii, such as at the inward-most position of the vertical bar a, the vertical pressure gradient is twice that at the 1,500-foot radius, indicating an excess upward force equal to gravity.

In the core region, closer yet to the axis, the trend is the opposite; that is, the vertical spacing between the pressure surfaces increases with decreasing radius indicating a lessening of the upward pressure force. This trend is illustrated by the vertical bars labeled c, all of which are the same length. This result corresponds with earlier findings [1] where upward current speed in the core region decreased with increasing altitudes above a certain level and there was an envelope of zero upward speed in near coincidence with the visible funnel cloud. And, as figure 1 indicates, the vertical pressure difference between the ground and 1,450 feet at the 1,500-foot radius is 51 mb. compared with only 23.5 mb. at the axis, a ratio of greater than 2 to 1. Using the assumption of vertical equilibrium at the 1,500-foot radius, the average upward force on the air at the axis between the ground and the 1,450-foot level is less than half that at the 1,500-foot radius, resulting in a net downward force there. Just the geometry of the situation indicates that if some of the isobaric surfaces intersect the ground while at some higher elevation they are level again, the vertical spacing between them over the region where they intersect the ground must be greater on the average than at some undisturbed region. The net downward force on the air in the core region of the tornado could mean a downdraft in some extent of the core, somewhat as shown by Ward's [5] model air vortex, or, more specifically, a downdraft inside of an updraft.

Figure 2 shows two alternative schemes of vertical air flow suggested by the isobaric analysis of figure 1 and by analyzing debris and cloud element movements in tornado movies and debris distributions in still pictures. It is suggested here that the core air acted on by a net downward force is at times frictionally supported above the ground by the upward jet as in figure 2a, or, occasionally not quite supported as in figure 2b; the latter would account for the wide trunk-type funnel sometimes seen touching the ground. Movies and still photographs of tornadoes have shown a clear region extending all the way to the ground from the bottom of the wide but suspended and chopped-off funnel, even though debris was being stirred up in the shape of a ring whose diameter is a little larger than the diameter of the chopped-off funnel. This could only happen when no air was flowing into the axis near the ground and would most likely happen with a downward flow diverging at the ground and keeping debris away from the axis.

The idea of a central downdraft is, of course, not new; Rossmann [6], Gutman [7], and Kuo [8] have all shown various theoretical systems of downdraft inside vortices. What is new here is the observation via movies of the lack of updraft along portions of the tornado trunk and in-

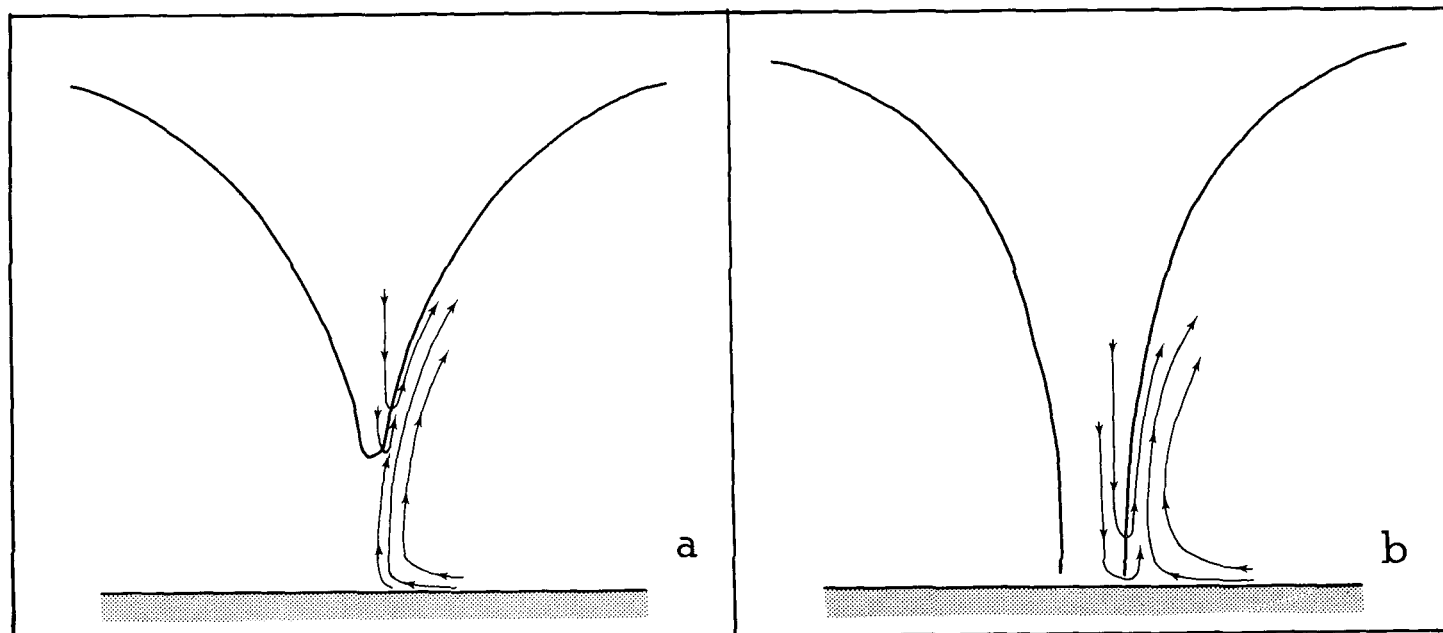


FIGURE 2.—Schematic air flow of the tornado in the radius-height plane as suggested by the results of figure 1 and the study of movies and still photographs taken of tornadoes. (a) Funnel aloft; (b) funnel reaching ground.

direct evidence of a downdraft from tornado still photographs.

#### 4. POSSIBLE REASONS FOR TORNADO GEOMETRY BEHAVIOR

Almost everyone is familiar with the various shapes that a tornado takes on, such as the suspended funnel, the rope-type, and the elephant-trunk-type funnel. Some of these differences in the shape and size of the tornado could be explained from the pressure profiles of figure 1 by assuming that the visible tornado surface lies along an isobar, and by varying the moisture content of the air involved in the tornado system. If the condensation pressure is specified to be 930 mb., the shape of the funnel would be that of the shaded portion of figure 3a, which is very much like some funnels aloft. If the condensation pressure is increased to 940 mb. the profile becomes like the shaded portion of figure 3b, which is still a suspended funnel but with the tip considerably lower. In figure 3c the condensation pressure is increased by only 5 mb. to 945 mb. and the tornado becomes a mature-appearing elephant-trunk type. For these small condensation pressure changes, the greatest dimensional change is in the tip height. For example, for the 10-mb. change from 930 to 940 mb. the tip drops 550 feet while the funnel cloud height at the 1,500-foot radius drops only about 125 feet. For situations with more steeply sloped and more tightly packed isobaric systems the tip movement would be even greater for the same change in condensation pressure. Between pressures of 945 and 975 mb. the trunk diameter for this tornado would become quite

insensitive to condensation pressure changes because of the tight horizontal packing of the pressure surfaces. However, relatively large changes would result in the diameter near the top of the funnel and in the height of the funnel at large radii for a given condensation pressure change.

At the time of the tornado, the condensation pressure at the Dallas Weather Bureau station was about 950 mb. This would require, with the pressure system of figure 1, a trunk diameter of 200 feet at the ground, yet the maximum diameter photographed was about 110 feet.

It is easily seen how the profile of the tornado can be changed rather drastically with only a little change in the water content of the air involved in the vortex. A similar type of profile change would result if the entire system-wide pressure of the tornado changed but the spacing and shape of the isobars and water content were conserved. Again it must be assumed that the visible tornado surface lies along an isobaric surface. It would seem that in the weaker stage of the tornado only slight changes in system-wide pressure or moisture would cause the tip height to change rapidly, while in the elephant-trunk stage, taken to be a mature or powerful stage, large changes in system pressure or moisture content would make little change in funnel diameter and no change in tip height, but would make moderate changes in the height of the visible funnel surface at the larger radii and higher elevations. In the latter stage the tornado trunk is in a relatively stable condition. Observations by means of movies confirm that in the immature stage the tip does rise and dip rapidly and trunk diameter fluctuates; but once the trunk touches the ground and assumes the elephant-trunk

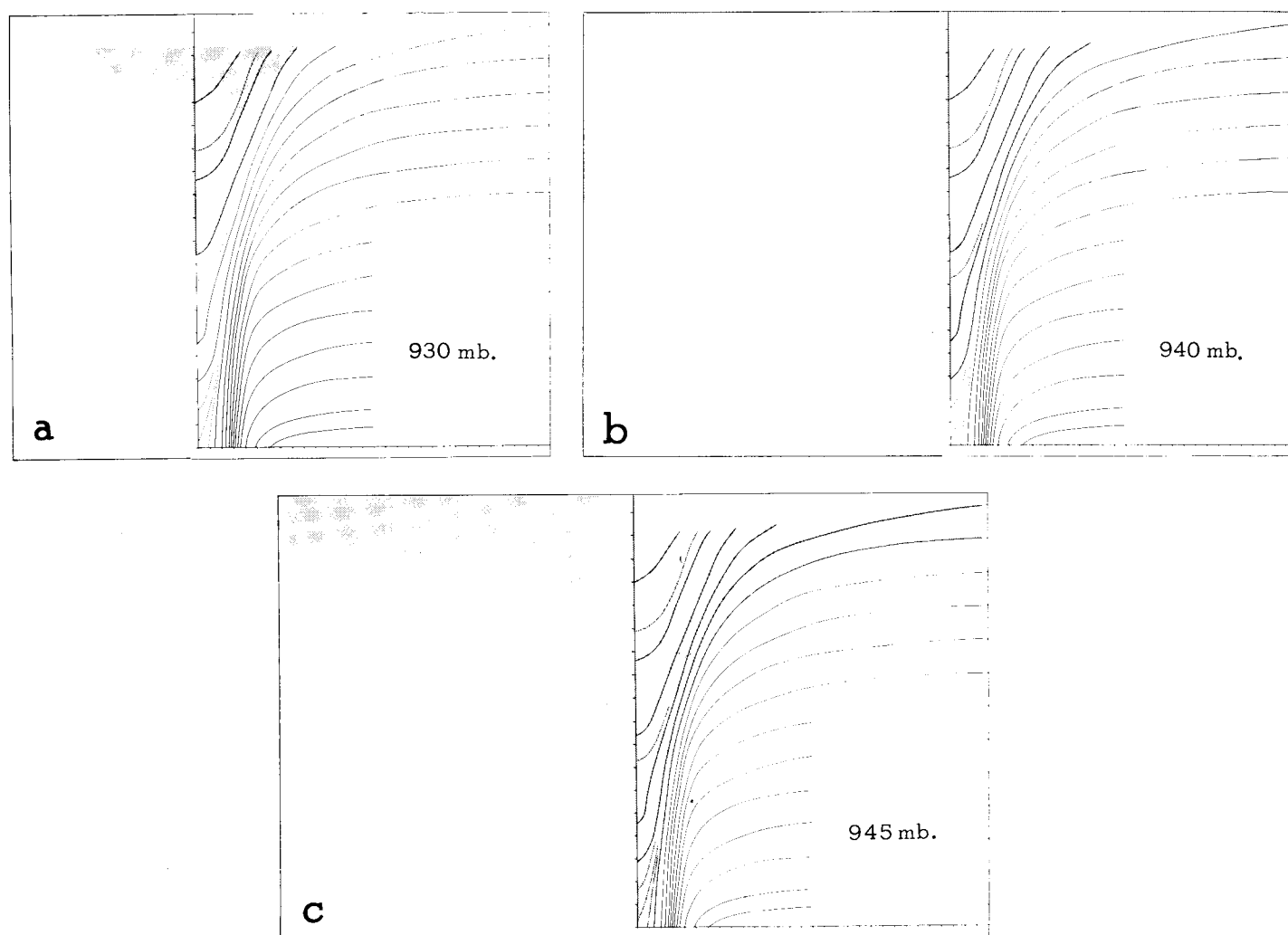


FIGURE 3.—Tornado funnel shapes for condensation pressures of (a) 930 mb., (b) 940 mb., and (c) 945 mb. for the Dallas tornado. Dimensional changes of the funnel are sensitive to condensation pressure change in the range from about 930 to 940 mb. and insensitive from about 945 mb. higher.

shape, rapid changes in trunk diameter no longer take place.

Additionally, shape changes could be effected if the system of isobars moved outward as a body. This would involve little additional central pressure drop since the radial rate of change of pressure near the axis at the ground is small, at least for this tornado. The result would be the wide, ominous-appearing tornado sometimes photographed and regarded as being particularly destructive. Likewise, if the system of isobars retaining the initial geometrical shape was crowded toward the center, with the water content conserved, the tornado would become tall and narrow, a rather frequent type of tornado that is photographed. In figure 4 are shown narrowed and widened tornadoes using the pressure surfaces from figure 1. In figure 4a and b the 940-mb. surface was used to provide suspended narrow and wide funnels respectively, and in figure 4c and d the 945-mb. surface was used

to provide narrow and wide ground-based funnels. Just what mechanism could effect such changes is not known but if the core of air excluded from the sink (observed in movies of the Dallas tornado and of the Scottsbluff tornado of June 27, 1955) were expanded or contracted in volume, it could cause the effects shown in figure 4. As an example figure 5 shows a series of photographs of the Wichita Falls, Tex. tornado of April 2, 1958, in the process of expanding. Note that the debris pattern in figure 5c is more dense along the outer edges but that it is clearer in the center beneath the truncated funnel. This arrangement can only indicate a shell-like dust pattern with a clear or clearer core. It is suggested that air converging toward the tornado, near the ground, turns upward in a shell whose diameter is nearly equal to that of the bottom of the funnel. This current carries the light debris upward around the edges and descending air (possibly descending slowly) from the tornado core assists in pushing aside the

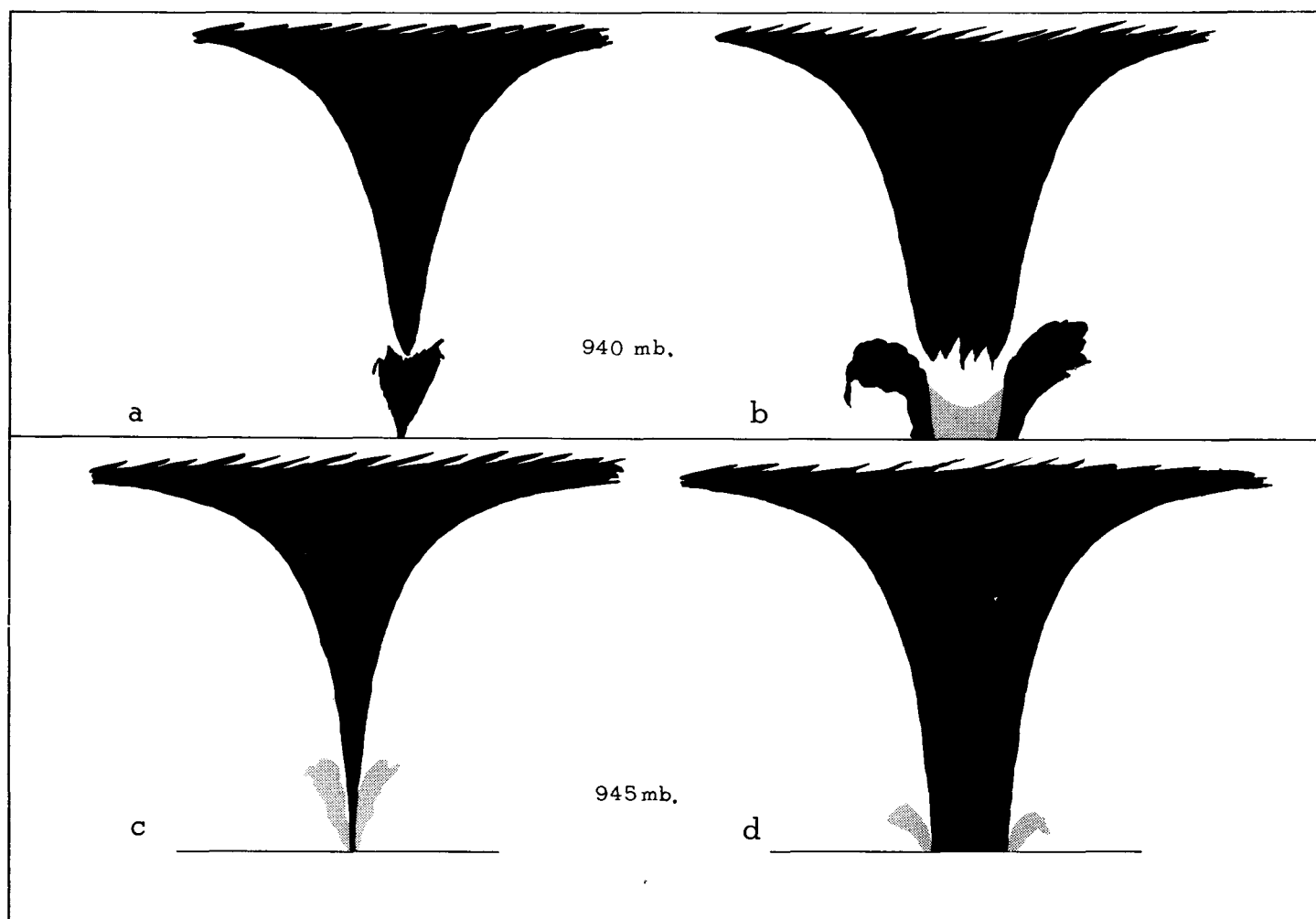


FIGURE 4.—The effect on funnel size of widening or narrowing the pressure field of the Dallas tornado using the pressure pattern of figure 1 and conserving the condensation pressure. (a) Narrow funnel and (b) wide funnel at 940-mb. condensation pressure. (c) Narrow funnel and (d) wide funnel at 945-mb. condensation pressure. The four profile types shown here are often photographed.

debris-carrying upward current. Ward's model [5] air vortex shows downdrafts under certain conditions.

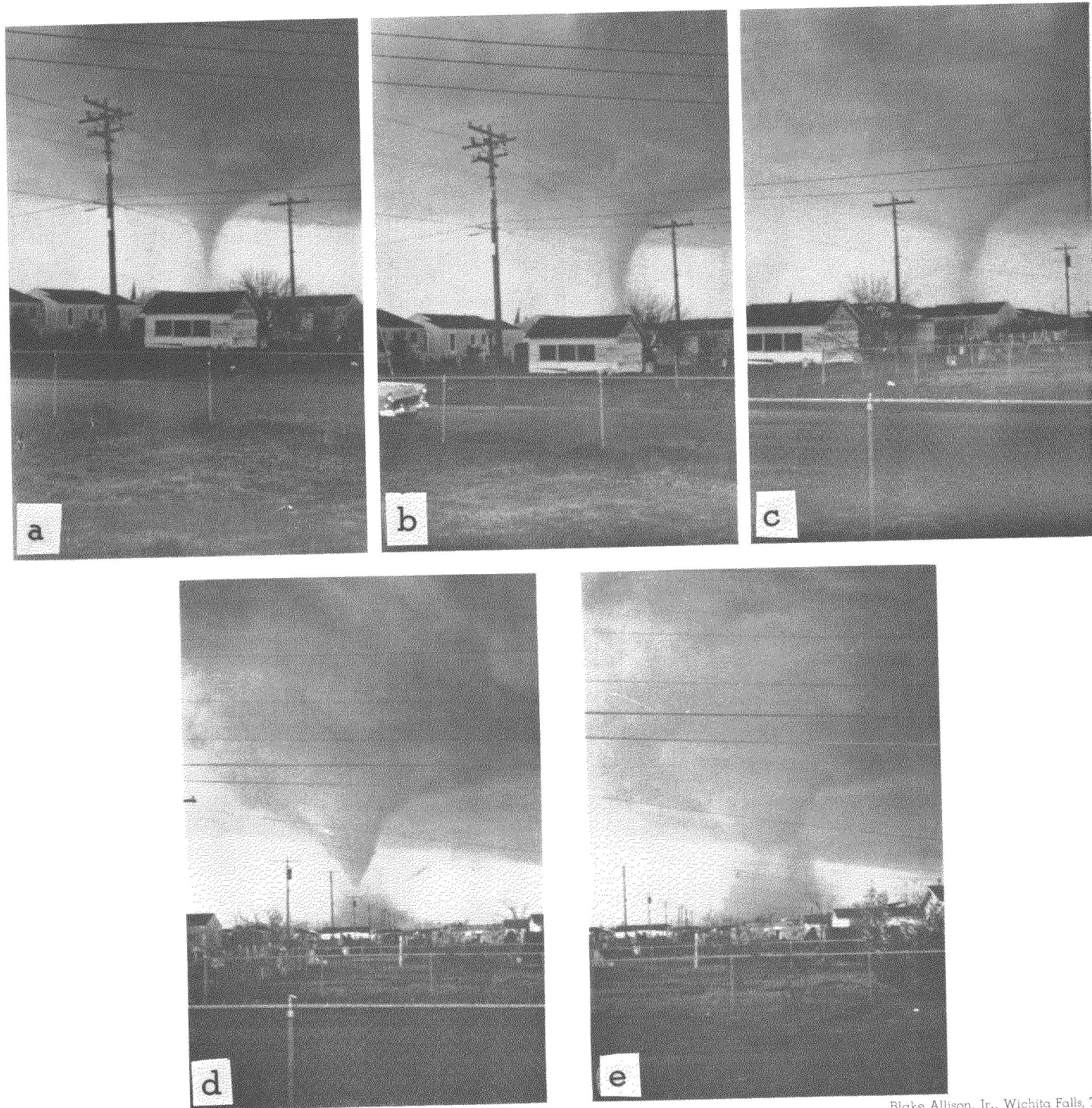
### 5. THE MOVING PRESSURE FIELD

Some interesting local pressure change variations result from translating the surface pressure field at 27 m.p.h., the average speed of the Dallas tornado. Figure 6 shows the rate of change of pressure at a point directly on the tornado path. In the computation finite differences were used, then center points were connected by a smooth curve. The starting point, zero seconds, is at the 1,500-foot radius, a distance from the tornado center at which little time-rate of pressure drop is encountered. For the first 19 seconds the rate of pressure drop averages about 0.1 mb. per second. Between 19 and 30 seconds it averages about 0.3 mb. per second. After the 30th second the pressure falls rapidly and by the middle of the 33d second reaches a peak rate of 26 mb. per second. The rate of pressure fall decreases rapidly after the 33d second and

returns to zero at the center of the tornado. As the tornado moves onward the sequence occurs in reverse order, assuming that the pressure field is symmetrical.

Much of the tornado damage described in the literature is attributed to the external pressure drop caused by the pressure field of the tornado. This assumes, of course, that the structures withstood the excessive wind speed experienced up to the time of the yield caused by excess pressure trapped in the structure. The rapid rate of change of surface pressure described above has applications to structures relative to the possible explosive force caused by the sudden external pressure drop. Now for the first time the effect on a structure can be quantitatively estimated since the pressure field presented here is in the nature of an observation, although an indirect one. An airtight structure is assumed in the following discussion.

Referring to figure 6 it is seen that the maximum rate of pressure increase (inside of a structure) of 26 mb. per second occurs over a period of 0.5 second. This computes



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FIGURE 5.—Photographic time sequence, (a) through (e), of the Wichita Falls, Tex., tornado of April 2, 1958, in the process of expanding radially. Note that the debris cloud near the ground expands from (d) to (e) at the same time and that the debris density in (e) is greatest along the outer edges.

to 26 pounds force per square foot increase in 0.5 second, and for a hypothetical 8 x 15-foot wall, 3,100 pounds increase in force in 0.5 second. And this is at the end of a period of additional rapid force increase.

To illustrate the total static pressure fluctuation at the ground along the tornado's path and adjacent to it (and total force on the hypothetical 8 x 15-foot wall), figure 7 was constructed. At the bottom is the time scale for 27 m.p.h., at the top is the equivalent distance scale along the tornado path, at the left is the percent of total pressure drop and at the right are scales of total pressure force on the wall and force per foot of perimeter. The left curve is the pressure variation along the path, the middle curve is that 100 feet from the path, and the right curve is the pressure variation for a location 150 feet from the path. The curves represent the pressure difference between an undisturbed region and any point within the tornado pressure field. Due to the crowding of the isobars between 100- and 150-foot radius, there is only 13 percent less final static pressure drop at a point 100 feet away from the center than is found directly on the path. However, the final pressure drop 150 feet away is 50 percent of the final on-path pressure drop.

Two analytical expressions were used to approximate the pressure-time profile of this tornado at the surface; one was for the 1500 to 300-foot radial distances (37.9 to 7.6 sec.) and the other for the remainder of the distance to the minimum pressure axis. These were:

$$p = 1 - \exp(-0.755/|t|), 7.6 \text{ sec.} \leq |t| \leq 37.9 \text{ sec.} \quad (2)$$

$$p = 1 - \exp(-48.3/|t|^3), |t| < 7.6 \text{ sec.} \quad (3)$$

in which the reverse time equivalent of distance was used, that is, time decreased to zero at the axis in making the computations. In both cases the curves were forced to pass through the observed point at 300-foot radial distance (7.6 sec.).

The fit of these analytical expressions is shown in figure 7 and is possibly better for the one covering the range of larger radii. The break in curvature at about the 300-foot radius reflects the sudden change in shear of the tangential wind speed found in an earlier work [1] and, of course is reflected in the balanced pressure field distribution. In the figure the x's are points computed from equation (2) and the +'s are points from equation (3).

Returning to the idea of the effect of the tornado pressure drop on a structure such as a dwelling, the author has been impressed by photographs of dwellings<sup>1</sup> with one wall popped off allegedly as a result of tornado proximity, and photos showing the common wall of a series of row houses or apartments removed intact leaving the rooms open to view and otherwise relatively undisturbed. Accordingly the scales at the right-hand side of figure 7

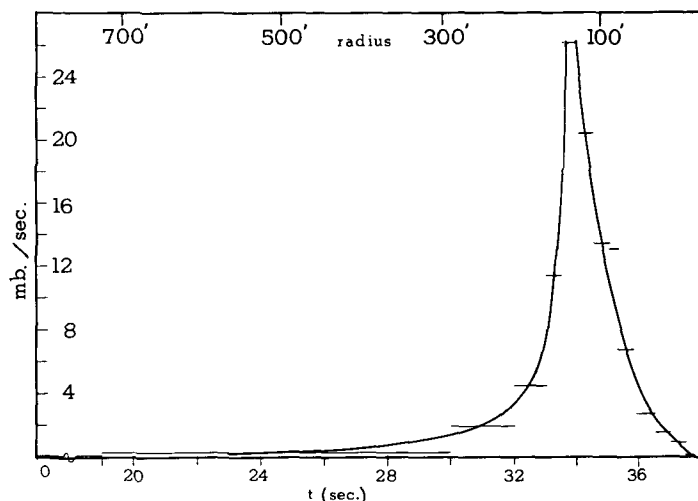


FIGURE 6.—The rate of change of surface pressure in mb. per sec. along the path of the Dallas tornado. The tornado axis is at the right.

have been computed to indicate the force on an 8 x 15-foot wall of a dwelling in the direct path, 100 feet away, or 150 feet away from the tornado. The force in pounds for any distance from the tornado center or position of nearest approach is given directly for all these paths. Another scale at the right shows the force per linear foot of the perimeter of the stated hypothetical wall. Note the tremendous force on the wall at the point of total pressure drop; it amounts to 7.5 tons and 85 percent of this force was applied in 5 seconds (in the Dallas tornado). For the house 150 feet away from the tornado path 7,500 lb. are applied at the point of nearest proximity of the tornado, or only about 50 percent of that for the structure directly on the path.

Now, suppose that the wall in question were nailed around its perimeter with two 20-penny nails per foot of perimeter. The pulling strength of a 20-penny nail was quoted as 70 lb. [10]. So for this hypothetical wall a force of 140 lb. per foot of perimeter would cause it to yield, theoretically. The yield point of this wall is shown at the solid black triangle opposite the last scale on the right of figure 7. The force on the wall for structures directly on the path as well as those 100 feet away greatly exceeds the yield point of this hypothetical wall. However, the wall for the dwelling 150 feet away at closest approach has nearly enough strength to resist the force of pressure drop; moreover, there the force is applied at a slower rate. A dwelling 175 feet from this tornado would encounter only 33 percent of the total pressure drop (100 lb./ft.) and so would not encounter the yield force.

Of course, no dwelling is airtight by the nature of the usual construction practices, and many dwellings are required by building codes to have attic vents at least. Such designed and inadvertent vents could prevent the

<sup>1</sup> Some examples are shown by Reynolds [9].

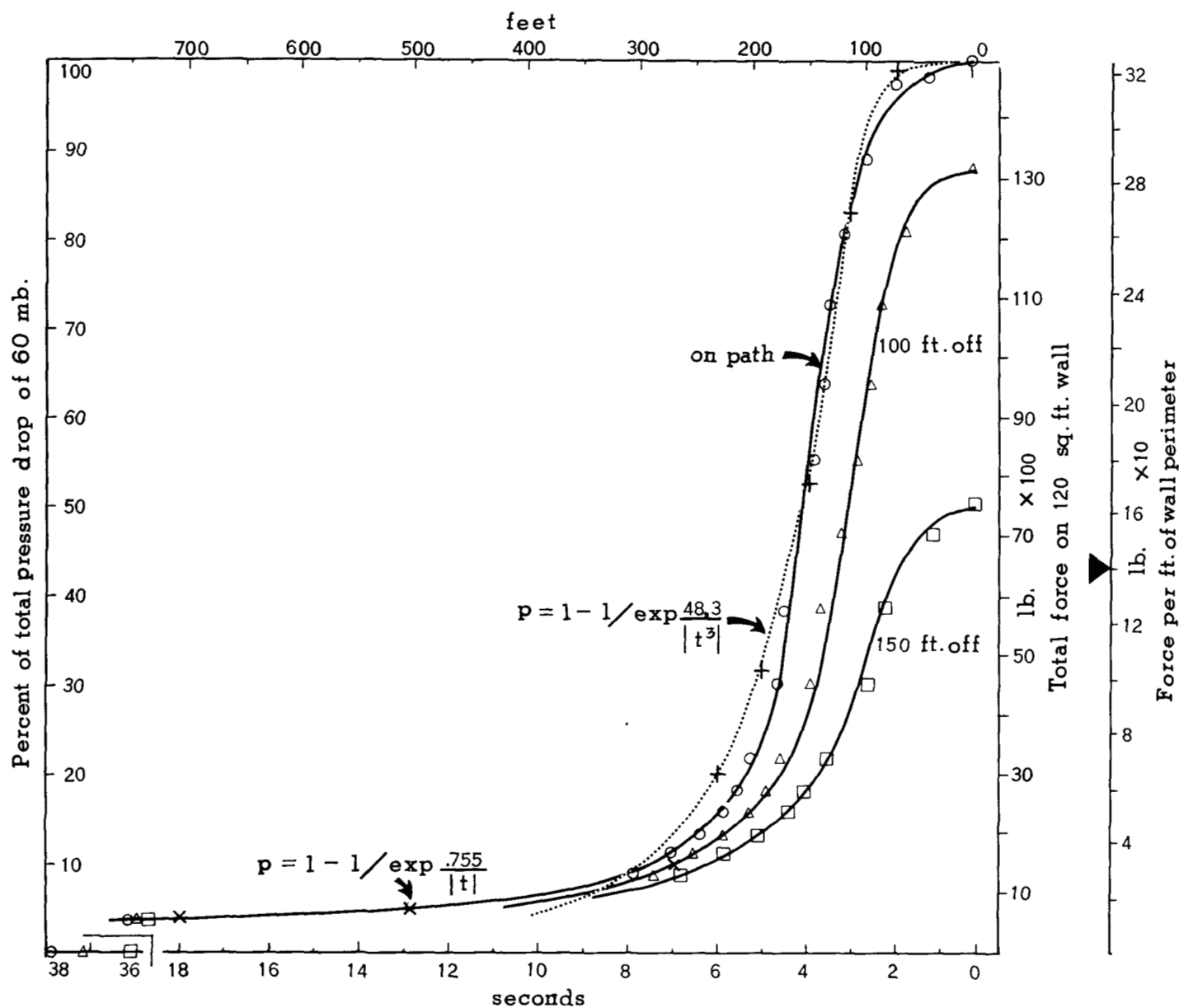


FIGURE 7.—Time (distance) variation of the Dallas tornado surface pressure drop “on” and “off” the tornado path in terms of percent of total pressure drop and force on hypothetical wall. An estimated yield point for the wall is indicated by the solid triangle on the right-hand scale.

build-up of certain amounts of excess pressure in dwellings, but just how much has always been the critical question. The answer depends upon the rate of drop of the environmental pressure at the building and the rate at which excess internal pressure could escape. Reynolds [9] has long been a strong advocate for installation of vents in dwellings for the purpose of releasing excess internal pressure that could result from the near approach of the tornado.

Having the time-rate of pressure change of the Dallas tornado, the effect of the pressure change on a hypothetical dwelling with a vent was examined. Pressure was to

bleed off exponentially at a rate that would remove nearly 75 percent of any imposed excess pressure in 5 seconds. The expression for the bleed or decay function was:

$$R = R_0 \exp(-at) \quad (4)$$

where  $R$  = residual pressure difference and  $R_0$  = initial imposed pressure difference. The computation was handled stepwise, as explained in the appendix, and was made only for the on-path case since it was found that the maximum accumulated pressure did not exceed the yield point of the hypothetical wall discussed earlier. The

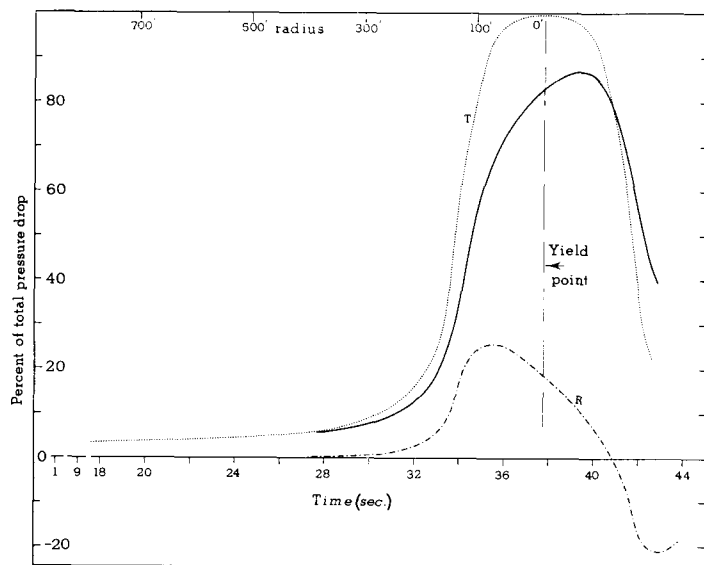


FIGURE 8.—Time variation of residual pressure difference between environment and interior of vented hypothetical dwelling (the dot-dash curve,  $R$ ). The environmental pressure (tornado pressure) is shown by the dotted curve ( $T$ ) and the solid curve represents the internal pressure of the vented dwelling relative to an undisturbed atmosphere.

results are shown in figure 8 where part of the pressure effects for the retreating side of the tornado are also shown. Here the dotted line labeled “ $T$ ” is the on-path pressure-time (distance) curve of figure 7 or the pressure drop in the tornado compared to the undisturbed region, the solid line is the pressure in the dwelling compared to the undisturbed region, and the dot-dash curve marked “ $R$ ” is the residual pressure, relative to the tornado, in the dwelling. The arrow marks the yield point of the hypothetical wall and it is noted that the maximum of the residual pressure curve falls below the yield point. The residual pressure relative to the tornado is virtually zero up to 30 seconds elapsed time, or 8 sec. before the axis of the tornado arrives. It rises sharply from 33.5 to 34.5 sec. then falls from 36 to 42 sec. These results appear to show a definite value in adequate venting. Of interest is the fact that the maximum residual pressure in the house is reached  $2\frac{2}{3}$  sec. before the axis of the tornado reaches the dwelling. The rate of external pressure drop decreases at that time so the bleed is able to prevent the yield pressure from being reached. Also of interest is the fact that the internal pressure in the dwelling is equalized relative to the tornado 3 sec. after the axis of the tornado passes, then actually becomes less than that of the tornado so that there is an inward force on the dwelling. Then 5 sec. after the tornado passes the internal pressure again starts to equalize as shown by the minimum point of the  $R$  curve. The solid curve also represents the time-lag of pressure drop, relative to an undisturbed environment, incurred by the interior of the house.

## 6. CONCLUDING REMARKS

For the first time tornado pressure data in the nature of an observation, although indirectly derived, have been used as a possible explanation for the changing shapes and sizes of tornado funnel clouds, for non-typical conceptions of tornado air flow, and for effects on airtight and vented hypothetical dwellings. It is realized that many factors have not been considered, such as the dynamic effects of the strong winds of the tornado that are felt about the same time as the pressure drop, and which might even neutralize some of the static pressure drop effects. The situation is not a simple one, but the first approach is better understood with a simple application. It is hoped that more usable data of this nature will become available so that they may be compared with the material presented here.

## APPENDIX

### METHOD OF COMPUTATION OF RESIDUAL PRESSURE VARIATION IN VENTED ENCLOSURES

The stepwise method of treating the pressure variations in vented enclosures was used here as an easy means of obtaining a reasonable estimation of the result wanted. Of course, such problems can be treated analytically when the imposed pressure variation is sinusoidal, a ramp or a step function, but the pressure-time variation imposed by the Dallas tornado was none of these. Accordingly, the stepwise method was used as described below.

The exponential decay function given by equation (4) was employed in the form:

$$R_1 = R_0 \exp(-a \Delta t)$$

where  $R_1$  is the residual pressure difference after a time interval  $\Delta t$ ,  $R_0$  is the total pressure difference at the initial time for each step,  $a$  is the coefficient that controls the

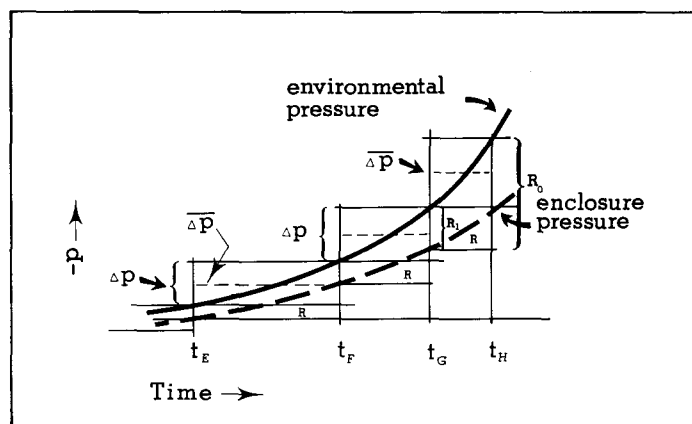


FIGURE 9.—Schematic illustration of stepwise method of computing pressure variation in a vented enclosure. The residual pressure difference,  $R$ , is added to the average of the externally-imposed pressure difference ( $\Delta p$ ) used for the next time interval.

rate at which the imposed pressure difference is to be bled off, and  $\Delta t$  is the time difference in seconds. About 75 percent of any imposed stepwise pressure difference would be bled off in 5 sec. for  $a=0.25$ , which was used in the computations described previously.

Although pressure differences were treated as step functions in the above equation, the approximate average of the pressure difference was used for  $R_0$  since the pressure actually changed over a finite time period. The residual pressure difference,  $R_1$ , was added to the average pressure step used for the next succeeding interval. The method is illustrated graphically in figure 9.

#### ACKNOWLEDGMENT

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#### REFERENCES

1. W. H. Hoecker, "Wind Speed and Air Flow Patterns in the Dallas Tornado of April 2, 1957," *Monthly Weather Review*, vol. 88, No. 5, May 1960, pp. 167-180.
2. *Handbook of Photogrammetry*, American Society of Photogrammetry, 1952.
3. R. R. Long, "Vortex Motion in a Viscous Fluid," *Journal of Meteorology*, vol. 15, No. 1, Feb. 1958, pp. 108-112.
4. A. H. Glaser, "An Observational Deduction of the Structure of a Tornado Vortex," in *Cumulus Dynamics* (Proceedings of the First Conference on Cumulus Convection, May 19-22, 1959), C. E. Anderson (Ed.), Pergamon Press, New York, 1960, pp. 157-166.
5. N. B. Ward, "Temperature Inversion as a Factor in Formation of Tornadoes," *Bulletin of the American Meteorological Society*, vol. 37, No. 4, Apr. 1956, pp. 145-151.
6. F. O. Rossmann, "On the Physics of Tornado Processes," Alamogordo, N. Mex., Dec. 1958.
7. L. N. Gutman, "Theoretical Model of a Waterspout," [Teoreticheskaia Model Smercha] *Izvestiia, Akademiia Nauk, SSSR, Seriia Geofizicheska*, No. 1, 1957, pp. 79-93.
8. H. L. Kuo, "Dynamics of Convective Vortices and Eye Formation," pp. 413-424 of *The Atmosphere and the Sea in Motion*, Rossby Memorial Volume (B. Bolin, Ed.), Rockefeller Institute Press, New York, 1959.
9. G. W. Reynolds, "Venting and Other Building Practices as Practical Means of Reducing Damage from Tornado Low Pressures," *Bulletin of the American Meteorological Society*, vol. 39, No. 1, Jan. 1958, pp. 14-20.
10. E. P. Segner, Jr., "Calculations of Minimum Wind Velocity Causing Structural Damage in the Dallas Tornado," *The Dallas Tornado of 2 April 1957, Tornado Damage Surveys, Raw Data Report No. 2*, The A. and M. College of Texas, Department of Oceanography and Meteorology, College Station, Tex., August 1957.